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14. VALIDATION AND UPGRADING OF PHYSICALLY BASED MATHEMATICAL MODELS

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I appreciate this opportunity to talk to this select group about these issues. The subject is validation and upgrading of physically based mathematical models. There are a lot of terms that are going to have to be defined.

The previous speaker discussed validation from a totally different standpoint from the one I am going to address. He was looking at total validation of the simulation complex, which involves the motion-based system, the visual system, the transport delays—everything that affects the way a pilot perceives what is going on in the simulator. The starting point for all of these issues, however, is the mathematical model that drives all of these systems. And it is very difficult to determine what constitutes validity in terms of visual display or what constitutes validity in terms of motion-based display.

On the other hand, the determination of what constitutes validity in terms of a mathematical model is very straightforward: model validation is a systematic procedure for testing and modifying a simulation mathematical model to achieve the required level of fidelity in matching experimental data. So as a starting point in determining validation of an entire simulation complex, it makes sense to at least make sure the mathematical model on a standalone basis can be validated and then to go on and use the more subjective criteria he recommended for validation of the entire complex. So I am defining validation strictly from a standpoint of making sure the mathematical model that drives these systems has acceptable fidelity.

The steps in validating a mathematical model are as follows:

1. Establish acceptance criteria
2. Conduct flight tests and collect data
3. Conduct simulation tests and compare results
4. Analyzes discrepancies that exceed acceptance limits
5. Modify the mathematical model to reduce discrepancies so they are within acceptance criteria limits

I will go through each of these in more detail. The first step—the previous speaker made this point as well—is to establish the acceptance criteria. And that is very critical. It drives everything else from there on down. Once you have determined what is important to the missions you are trying to accomplish, then you can establish criteria to validate the model against those missions and then you can perform the rest of these activities: to conduct the necessary flight tests, and collect the data as a basis of comparison; to perform simulation tests in an appropriate fashion to run comparisons with the experimental data; to analyze any discrepancies between the simulation results and the flight-test results; and, when those discrepancies exceed the acceptance criteria limits, to modify the mathematical model to bring those discrepancies within acceptable limits. The latter is, of course, the most difficult task.

Let's start with acceptance criteria, the first part of the procedure (table 1). I am going to define validation in two different ways: functional validation and physical validation. To begin with, functional validation, or acceptance criteria to determine functional fidelity, basically requires fidelity of pilot cues. What you are trying to do is to make sure that what the pilot sees is an accurate representation of the input/out relationships of the aircraft. You don't care what is going on inside the mathematical model. It is a black box. All you are really interested in is that given the right input you are getting the right output. That is functional fidelity. And this, of course, is the primary way in which current training simulators are evaluated, on a functional basis.

The kinds of criteria that are used for functional validation are based on the effect, not on the cause. The response is being validated, not what is producing the response. The three classic criteria are trim, stability, and dynamic response. Regarding trim, you usually characterize the control settings required to trim the aircraft at different flight conditions. Often, stability is not specifically

Table 1. Acceptance criteria: functional fidelity

1.	Requires fidelity of pilot cues
2.	Functional criteria (validate effect)
	Trim
	Stability
	Response
3.	Tuning factors: empirical coefficients
4.	Scope of validation: validation at system level
5.	Bandwidth of validation: limited to handling-qualities range
6.	Amplitude of validation: limited to linear range

used as a criterion in the training industry. It is somewhat inherent in the response measurements, but stability characteristics could be prescribed either in the frequency domain or in the time domain. For the frequency domain, the phase or gain margins can be specified; for the time domain, the eigenvalues or eigenvectors can be specified. The dynamic response of the actual test vehicle can be compared both in the time and the frequency domains with similar responses for the simulation to determine whether the response is correct. This is often used in the training industry, at least in terms of time-domain responses. There is very little in the way of frequency-domain criteria that is being used right now for validation.

As far as the training industry is concerned, one of the major problems with the current acceptance criteria that have been established is that there is no attempt to specify how the manufacturer can tune the mathematical model to meet the acceptance criteria. The manufacturer basically has carte blanche to do whatever he needs to in order to meet those acceptance criteria. And typically what happens is the manufacturer will add empirical coefficients at appropriate places in the simulation that make it very easy to tune in order to satisfy the acceptance criteria.

I have seen a number of cases in which scale factors and biases have been added to aerodynamic forces and moments. It is nonphysical, but it accomplishes the job of satisfying the specific test criteria. The problem with this kind of manipulation is that because it is done totally empirically, it satisfies the criteria at the test points but there is no guarantee that it is going to give a realistic response outside the test points or between test points. Basically, the test curve that the government gives you to satisfy is being fitted, and you can't be assured that it is going to really represent the correct aircraft response. The other issues associated with the acceptance criteria are the scope of the validation. By this I mean is it end-to-end validation of the total aircraft that is of concern or is it the subsystems and their independent validation.

Typically, right now validation is performed at the system level only, and it is based strictly on the six-degree-of-freedom aircraft rigid-body motion. If that is accomplished, the basic idea is that that is what the pilot sees, that is what the pilot perceives; there is no reason to carry validation into any more depth than that. The problem with that, as we will shall see, is that it allows the manufacturer to tweak a subsystem, the tweaking of which may be totally inappropriate, in order to get the total response correct. If the rotor model isn't right, he may alter the control system in order to give the net response that is desired. By allowing validation at the global level, the manufacturer is given a lot of leeway in adjusting individual components, which in turn eliminates interchangeability and modularity of the resulting simulation.

Another major issue is the bandwidth of the validation, that is, the frequency to which the simulation must be accurate (table 1). And typically there have not been a lot of frequency-response criteria associated with training simulators. This is a major problem. The way in which it is evaluated, though, does predominantly limit the bandwidth to the handling-qualities range, which again assumes that that is all the pilot is going to see and all he cares about.

The last acceptance criterion, which is a really important issue, is the amplitude of the validation (table 1). Typically, people will limit the perturbations in the linear range. Validating the model when it is driven into its nonlinear range is a much more difficult job. There are virtually no acceptance test criteria that enforce driving the model into the nonlinear range to see if it is accurately represented. What you end up with is a training simulator that has been validated only in the middle of the envelope for mild maneuvering. If a pilot maneuvers it aggressively or flies to the edge of the envelope, the simulation and that environment based on these validation criteria have not been validated. And that is precisely where simulation should be particularly valuable, in conditions in which a pilot would not want to fly a real aircraft. That is typically not addressed in the validation criteria.

Let's take the other alternative, which is physical fidelity (table 2). By this I mean we are requiring that the mathematical representations of the physical phenomena in the simulation be correct. Instead of looking at the simulation as a black box where all you are interested in is proper end-to-end response, you are going to look at the way in which the phenomena are modeled and try to validate it to that level. This is typically done in engineering simulators. The main reason it has not been used in training simulators is because it is a much more difficult process, much more costly to do and to validate, and, ultimately, because it is very difficult to perform in real time, which is required for training in real-time simulations. What is happening right now, however, is that with the advent of parallel processing technology and modern high-speed computers, we can take physically based models and perform real-time simulation with them.

Computer technology has been developed to the point where we can start using physically based models for real-time training applications. As a result, we need to look at what the advantages are of this kind of modeling to the training industry. Again, the acceptance criteria in a physically based model are to validate the cause rather than the effect. Here what you are going to try is to compare applied loads for accelerations of the vehicle for given flight conditions. The way in which the model is tuned is much more restrictive than it is in a functional model. The only way the contractor is allowed to modify the system is to modify the structure of the mathematical model, in a physically meaningful manner, or to change physically meaningful parameters, not empirical coefficients. So it tremendously complicates the process of tuning the simulation to match the acceptance criteria.

The scope of the validation is another important issue. Now we are talking about validating the system at the subsystem level. It is not acceptable to think of this as just a black box—that as long as the right response is obtained, we don't care what goes on inside. You are now going to break the total model down to a main-rotor module, a tail-rotor module, horizontal stabilizers, and engines. Each of the components is going to be separately validated against independent test criteria so the control system can no longer be altered to make up for problems in the rotor model. The bandwidth of the validation now has to be significantly increased. And it has to be expanded to include the bandwidth of all modeled degrees of freedom in the system. If the subsystems are going to be validated with physically based models, it is necessary that the degrees of freedom of all the physically based models in the system be exercised. Of course, it is necessary to be able to excite it throughout the range, to be able to go into the nonlinear region and validate it there.

One of the benefits of going to physically based models is that it should make it possible to achieve global fidelity of the mathematical model; that is, you should be able to drive it to the edge of the envelope, fly it with aggressive maneuvering, and really use it as it should be used, as a tool for training a pilot in dangerous flying activities, those he could never achieve or even come close to, safely, in an aircraft.

The third item on the list was flight test and data acquisition (table 3). These have to be geared to the acceptance criteria. Once the acceptance criteria are established, data must be collected to support the performance of this acceptance test. What is done is to collect data associated with functional validation, trim data, stability

Table 2. Acceptance criteria: physical fidelity

1. Requires fidelity of mathematical representation of physical phenomena
2. Physical criteria (validate cause): applied loads/acceleration
3. Tuning factors
   - Model structure
   - Physically meaningful parameters
4. Scope of validation: validation at subsystem level
5. Bandwidth of validation: includes bandwidth of all modeled degrees of freedom
6. Amplitude of validation: excites nonlinear range

data, response data; typically this is limited to the airframe rigid-body motion.

Physical validation is a much more difficult problem. In order to isolate subsystems for independent validation, it must be possible to collect boundary data at each of the subsystems. For example, the reaction loads between the rotor and the fuselage must be measured so that the rotor can be isolated from the fuselage motion and validated as an independent subsystem. Typically, therefore, it must be possible to collect load data at the subsystem interface and to be able to collect acceleration rate and displacement data at subsystems. As a result, it is a much more difficult data-collection task.

The way in which this is commonly performed, or can be performed, is to use redundant sensors and kinematic constraints to eliminate the instrument, calibration, and procedure errors that are encountered. Too often raw test data with no cross-checking are used for acceptance test criteria. Our experience has been that such data are fraught with calibration errors and procedure errors. There are too many good ways available for doing consistency testing, kinematic cross-testing, for this to be the case. This should be used to ensure that you have the right experimental data to form the basis of the acceptance criteria.

The mass properties and the sensor geometry must be documented. It must be possible to perform maneuvers that span the bandwidth and amplitude of the validation criteria. For the closed-loop simulation, here for the simulation tests, there are two approaches. The purpose of the closed-loop simulation is basically to initialize the simulation to the starting test conditions, drive it with test control inputs, and then compare its response with the dynamic response of the test (table 4).

This is the way in which it is ordinarily done. The advantage is that it is simple to implement and requires minimal sensor data. The disadvantage is that you have a cumulative buildup of error and you cannot isolate subsystems because of the coupling between them. The open-loop approach to testing the simulation is to disable the airframe rigid-body motion and drive the simulation with the control inputs and the rigid-body motion that has been

Table 3. Flight test and data collection

1. Functional validation
   Collect trim, stability, and response data for airframe rigid body degrees of freedom
2. Physical validation
   Collect loads data at subsystem interfaces and acceleration, rate, and displacement data at subsystems
3. Perform data consistency tests with redundant sensors and kinematic constraints to eliminate instrument calibration errors and procedural errors
4. Document mass properties, sensor geometry, and atmospheric conditions during tests
5. Perform maneuvers that span the bandwidth and amplitude of the validation criteria

Table 4. Conduct simulation tests and compare results

Closed-loop simulation
1. Method
Initialize simulation to starting test condition
Drive simulation with test control inputs
Compare dynamic response of simulation to dynamic response of test
2. Advantages
Simple to implement
Requires minimal sensor data
3. Disadvantages
Cumulative error build up due to closed-loop integration limits validity of comparison
Coupling between dynamic subsystems limits ability to isolate discrepancies

determined from the test data (table 5). So what you are really doing now is driving the simulation on in a dynamic wind-tunnel mode and looking at the loads that are produced along the same flight trajectory that the aircraft produced. You compare these loads with those obtained from the flight to validate the model. The advantage is that it eliminates cumulative error buildup and it allows the subsystems to be validated independently. The disadvantage is that it is much more difficult to implement, and more expensive data are required to isolate the loads at the subsystems.

For the analysis and modification methods there are two primary objectives: model structure has to be established and the parameters have to be modified (table 6). And the kinds of modifications you will typically have to make are to add coupling, higher-order dynamics, and nonlinearities.

The parameter identification method used for linear-parameter dependency can be regression. The more difficult problem of nonlinear dependencies would require an output-error approach. The point I have been making all along is that training simulators are functionally validated. The validation is performed at the system level with the rigid-body airframe response as the validation criterion. Satisfaction of this criterion is achieved by tuning empirical coefficients. The result is a model tuned for specific conditions that has been validated only for bandwidth low-amplitude maneuvers (table 7).

The bottom line is that validation requirements drive the modeling sophistication (table 8). You get what you ask for. And the simulation manufacturers will not produce the physically based simulation if the validation requirements are functionally based. For example, rotor-map models are functional approximations to the blade-elements model; they satisfy acceptance test criteria as currently specified. However, you could specify criteria in a form such that contractors would have to go to a blade-elements model in order to achieve your requirements. In conclusion, what I think is really needed is a standard for rotorcraft validation that in a sense is like the standard that

Table 5. Conduct simulation tests and compare results

Open-Loop simulation
1. Method
Disable integration of airframe rigid-body motion in simulation
Drive simulation with control inputs and rigid-body motion from test data
Compare loads/accelerations of simulation with test data
2. Advantages
Eliminates cumulative error build up due to integration of airframe states
Allows subsystems to be isolated and validated independently
3. Disadvantages
Implementation of simulation run is more difficult
More extensive test data are required to isolated loads at subsystems

Table 6. Analysis/modification methods

Model structure determination
1. Correlate errors to states and controls for nominal parameter values
Statistical correlation of error
Frequency response of error
2. Postulate modification to model structure
Additional coupling
Higher-order dynamics
Nonlinearities
3. Repeat comparison step and iterate until error can be sufficiently limited by reasonable parameter changes

Table 7. Problems with current validation approach

1.	Validation is only guaranteed in vicinity of test points
2.	Low-bandwidth validation does not support aggressive maneuvering, high-speed flight, or high-gain controllers
3.	Low-amplitude (linear) validation does not support aggressive or edge-of-the-envelope maneuvers
4.	Lack of subsystem validation eliminates modularity and interchangeability in subsystem models

Table 8. Validation requirements drive modeling sophistication

You get what you ask for
Simulation manufacturers will not produce physically based simulations if the validation requirements are functional
Example:
Rotormap models are functional approximations to the physically based blade-element model
They satisfy trim and stability requirements and low-bandwidth response requirements for function validation
They will not satisfy a validation criteria that specifies rotor impedance (rotor load frequency response to hub acceleration)

Table 9. Rotorcraft validation standard

A standard for rotorcraft validation is required that will address the following:

1. Acceptance criteria versus simulator mission requirements
2. Flight-test procedures and instrumentation versus acceptance test criteria
3. Generation of simulation data and comparison with flight data
4. Model structure determination and parameter identification methods for reducing errors to specified limits
5. Acceptable physically based parameters for tuning and their allowable range of variation

we are addressing here this week for simulation qualifications (table 9). It could be either a part of the simulation qualifications or be detailed enough to require a separate specification.

We have to define the acceptance criteria as a function of the mission requirements. We have to determine flight-test procedures and instrumentations in order to be able to implement acceptance criteria. We have to be able to generate the simulation data and compare them with flight data in a systematic manner, apply modern tools for model structure determination, and parameter identification for achieving the criteria. Then we have to determine what physically based parameters are acceptable for tuning the simulation and what is their allowable range of validation. These are all terms that should be defined in a specification so that validation can be standardized.

MR. WALKER: Since the interface between the subjective evaluator and the mathematical models is really the simulator that is provided by visual systems, motion bases, audio systems, and so on, how do you resolve the errors that may be introduced by these systems in the development of your validation?

MR. DU VAL: I am referring strictly to the validation of the mathematical model; my contention is that you should not compensate for errors in these other systems by modifying the mathematical model; you should put in compensations for the systems, where they belong, that is, within the systems.

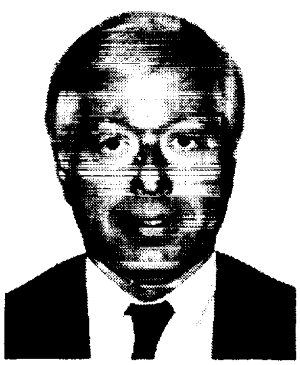
MR. HAMPSON: I agree entirely with you. I do have some difficulty, though, with some of the comments you made with respect to tweaking the model. I don't know if this is particularly a helicopter problem you are addressing, but certainly with fixed-wing and also with the helicopter models that are provided by the aircraft manufacturer, we, as a simulator manufacturer, do not tweak the models. We identify the deficiencies and go back to the aircraft manufacturer and tell him there is something wrong with his model or have him explain to us why we have a problem. And I think that is the proper way to do things, rather than expecting the simulator manufacturer to tweak a model.

It goes back to something I said yesterday, but in the helicopter world we rarely get a model from the manufacturer of the aircraft. That is a significant issue, I think.

MR. DU VAL: That is true. I haven't really made the distinction of whether the mathematical model was generated by the simulator manufacturer or the aircraft manufacturer. The point is if the physically based mathematical model does not match the acceptance criteria, to add empirical parameters to make it match the criteria is not an appropriate solution, that it must be physically modified.

MR. GALLOWAY: You mentioned that you get what you ask for. I would like to add the comment that you get what you pay for or are willing to pay for. How do I convince my Navy program managers to pay for the efforts you advocate for getting the data?

Mr. DU VAL: The answer is modularity. You are going to pay for it in the short term, but you are going to get your money back in the long term. If you validate the subsystem models at the subsystem level, then you have interchangeability of mathematical models. You can plug in rotor models, you can build on them, because you validated each of these components separately. It provides for the kind of modular interchangeable mathematical modeling for simulation that we have been striving for. Once you have validated the basic component it is only a matter of changing the physical attributes to validate it with a different aircraft. So even though it is more costly to do this up front, it is going to reduce the cost of validation on future simulation activities because you have building blocks you can work from.



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